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Long-term nitrogen use and nitrogen-removal index in continuous crops and rotations

Charles F. Yamoah [a,*], Gary E. Varvel [a,b], William J. Waltman [c], Charles A. Francis [a]

[a] Department of Agronomy, University of Nebraska-Lincoln, Lincoln, NE 68583-0949, USA
[b] USDA-ARS, 123 Keim Hall, University of Nebraska-Lincoln, Lincoln, NE 68583-0910, USA
[c] USDA-NRCS, Federal Bldg, 100 Centennial Mall N, Lincoln NE 68508-3866, USA

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Abstract

Cropping systems, nitrogen (N) fertilizer levels, and climate largely dictate patterns of N use and influence problems arising from N fertilization. Nitrogen use was assessed in cropping systems with a nitrogen removal-index (NRI), defined as the ratio of N removed in the grain to total N supply including that from N fixation by legumes grown in rotation. Results are reported from analyses of NRIs of cropping systems that comprised a 12-yr continuous and sequential growing of maize [*Zea mays* L.], soybean [*Glycine max.* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and oat/clover [*Avena sativa* (L.)/80% *Melilotus officinalis* (L.) Lam., 20% *Trifolium pratense*] in eastern Nebraska. Rotations involving maize or sorghum had higher NRIs than continuous cereals at 0 N application levels. Increasing N rates reduced NRI and resulted in an increase of residual nitrate in all but the continuous soybean system. Also, NRI was highest in continuous soybean, lower in continuous maize, and lowest in continuous sorghum. Rotations and lower N rates both contributed to higher NRI and lower soil residual nitrate. Biological windows that comprised the cumulative number of days in the entire year when soil is moist and temperature above a specific threshold correlated positively and significantly with NRI, whereas NRI and August temperature were negatively related. Between 43 and 87% of variability of NRI in maize and soybean systems was attributed to August temperature plus August precipitation index. Biological window (moist soil, temperature above 5°C) plus May temperature explained up to 76% of variability of NRI of maize and soybean. Nitrogen removal index for sorghum was unrelated to weather variables. Estimated additions to the soil organic N reserve from the return of crop residues averaged between 16 and 80 kg ha^{-1} yr^{-1} with higher levels from sorghum and from all treatments with high levels of N fertilizer. Crop rotations generally increased the N-removal index, reduced the year-to-year variability in N-removal-index, and at 0 N-application rate, increased the return of N in residue to the soil N pool, compared to continuous cropping of single species. © 1998 Elsevier Science B.V.

Keywords: Nitrogen-removal index; Biological window; Cropping systems; Maize; Sorghum; Soybean

1. Introduction

Nitrogen (N) fertilization increases crop yields where N supply limits crop production, but may cause environmental problems if the amount applied

* Corresponding author. Fax: +1-402-472-4104; e-mail: csas004@unlvm.unl.edu.

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exceeds crop demand, and N volatilization, leaching, or surface erosion occurs. Management decisions, such as level of fertilization, crop selection and sequencing, as well as climatic forces largely control efficiency of nutrient utilization in cropping systems, and thus the extent to which N fertilization contributes to environmental pollution. An efficient cropping system should neither deplete the soil of major nutrients, nor result in excess accumulation in the soil that increases the potential for contamination of underground and surface water. Growing several species of crops together or sequentially may utilize nutrients more efficiently than monoculture if the different species exploit a larger soil volume or different parts of the profile (Francis, 1989). Additionally, the large and diversified plant mass returned to fields under appropriate rotations can improve soil quality and promote root and microbial activities (Barber, 1972; Baldock et al., 1981; Bruce et al., 1990). These attributes stabilize the soil, lead to more efficient exploitation of applied and native nutrients, and contribute to higher economic returns.

Nitrogen-uptake indices have been developed for various agronomic systems. Moll et al. (1982) applied their index to evaluate genotypic variation of maize in response to N supply. A technique to separate N fixation from the total legume contribution in a legume–cereal sequential cropping system was elaborated by Russelle et al. (1987). Using a hypothetical example, Russelle et al. (1987) found that 62% of the increase in maize yield following alfalfa was due to N supplied by the legume. The remaining 38% was credited to other benefits of rotation. Huggins and Pan (1993) adopted and expanded the models of Moll et al. (1982) and Russelle et al. (1987) to design a new approach that incorporated additional soil and plant variables that cause differences between cropping systems. The new concept known as nitrogen-efficiency component analysis was applied to a case study of hard red spring wheat under two tillage systems. The component analysis of Huggins and Pan (1993) recognized the various sources of N in total soil N pool as described by Meisinger (1984). The literature cited by Pierce and Rice (1988) noted a dearth of information on the impact of rotations on N use, and the authors expressed the need for further work based on an approach that considered the total soil N pool.

One objective in the present work was to apply portions of the N-uptake models of Huggins and Pan (1993) and Meisinger (1984) in a quantitative analysis of N-removal indices (NRI) of cropping systems, and evaluate the significance and utility of such an index in comparing cropping systems. For this analysis, data from a 12-yr comparison of sequential and continuous growing of maize, soybean, grain sorghum and oat/clover in eastern Nebraska was used. The second objective, using the same data set, was to determine the effects of climatic factors on year-to-year variability of NRI as a measure of system stability. The rationale is that a better understanding of the mechanisms of N use by crops will aid in designing more nutrient-efficient management strategies for rotations.

2. Materials and methods

2.1. The experiment

The experiment was conducted from 1984 to 1995 under rainfed farming conditions at the Agricultural Research and Development Center (ARDC) near Mead, a site typical for eastern Nebraska (41°N, 96°W). The soil type is Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudoll; USDA taxonomy) with initial organic matter content of 31 g kg^{-1} in the upper 75 mm (before experiment, 1984). The experimental design was a split plot with five replications. The seven main plots were assigned to seven cropping systems as follows.

Continuous cropping:	(M) maize
	(G) grain sorghum
	(S) soybean
2-yr rotations:	(M–S) maize–soybean
	(G–S) sorghum–soybean
4-yr rotations:	(M–S–G–O/Cl) maize–soybean–sorghum–oat/clover
	(G–S–M–O/Cl) sorghum–soybean–maize–oat/clover

Rotations were chosen to compare the modal 2-yr maize–soybean and sorghum–soybean systems currently grown in this area with 4-yr rotations that would further diversify the enterprise mix and potentially contribute to greater yield and income stability on farm. Subplots consisted of three levels of fertilizer N added to each crop: 0, 90 or 180 kg N ha^{-1} for maize and sorghum; and 0, 34 or 68 kg N ha^{-1} for soybean and oat/clover. The oat intercrop with clover constituted a single year in the 4-yr rotations. Oat was harvested as feed grain during that year while the clover was allowed to continue growth into the fall. It was incorporated into the soil as green manure, using a tandem disk, in mid- to late April of the following year.

Main plot size was 9 × 32 m and subplot size was 9 × 10 m. Maize was seeded at 47,000 seeds ha^{-1} in the first week of May. Grain sorghum was seeded at 170,000 seeds ha^{-1} during the last week of May and first weeks of June. Seeding rate for soybean was 370,000 ha^{-1}, and this was sown from mid-May to early June, depending on conditions each year. The maize, grain sorghum and soybean cultivars were changed in the course of the study. A mixture of sweet and red clover ['Madison' sweet clover (80%); red clover (20%)] was used to guarantee adequate biomass in the 4-yr rotations. Crop residues were disked just before sowing of each crop. Seeding was done with a six-row planter to achieve the 12-row plots, and each crop in every rotation was in the field in each of the 12 years. Other routine cultural practices and combine grain harvest procedures for the middle rows of each plot were reported by Varvel and Peterson (1990).

2.2. Sample harvests and N analyses

Five representative plants from each subplot sample were cut, weighed, and dried for dry matter determination and N uptake. Ground subsamples of straw and grain were analyzed for total N with a Carlo Erba Model 1500 CNS Analyzer (Carlo Erba Strumentazione, Milan, Italy). After combine harvest of the crop in October, soil samples (0–15 cm) were collected to determine residual soil inorganic N. A 0–15 cm sampling depth was used because previous studies at the same site detected insignificant amounts of residual nitrate below that level to depths of 7.5 m (Varvel and Peterson, 1990). Samples were air-dried, ground, and analyzed for 1 M KCl-extractable NH_4–and NO_3–N with a Technicon autoanalyzer using phenate and brucine procedures, respectively (Keeney and Nelson, 1982).

2.3. Soil N supply

The supply of N available to the crops from the soil was calculated according to the Huggins and Pan (1993) model:

$$N_s = N_f + N_r + N_m + N_x + N_d. \quad (1)$$

where N_s = total soil N supply, N_f = fertilizer N, N_r = residual inorganic N before cropping, N_m = mineralized N, N_x = fixed N, and N_d = N deposited from the atmosphere, irrigation and run-on.

They simplified the above relationships to accommodate use of routine data in two steps: (1) $N_s = N_f + N_r + N_m$ (N_r and N_m from control N plots), and (2) $N_r + N_m = N_t + N_h$, where N_t is aboveground N at harvest and N_h is soil inorganic N remaining after harvest (all terms from control plots). Assumptions stated by Huggins and Pan (1993) to the use of control plots to calculate N_s were: (1) applied N does not influence gains or losses of available N from other N pools; (2) no losses of residual available N, mineralized N or other forms of N occur in the control plots; (3) other inorganic N inputs are minimal and are captured in the estimate of mineralized N; and (4) total N supply is underestimated because of N immobilized from the control plots. In the formulation of NRI, it was further assumed that N fixation by the legumes can be considered as part of N_m and soil N supply. It is obvious that a dynamic activity such as entry into and extraction from the soil N pool is complex and not easily quantified. For example, larger levels of fixed N in the current systems with legumes are distinguished from the lower levels in the wheat systems of Huggins and Pan (1993). Nonetheless, formula (1) provides an approximation of the relevant components that make up total N supply (N_s).

2.4. N removal index (NRI)

Yearly N removal indices were calculated for continuous monocrops, 2- and 4-yr rotations for cropping system combinations of maize, sorghum, soybean and oat/clover at zero N, low N and high N rates in 12 years. Nitrogen-removal indices were calculated for each cropping systems as the ratio of N removed by crops to total soil N available to crops. The calculations embraced data for the entire cycle of each rotation and each N level. As a generalized illustration, a maize–soybean rotational sequence consists of maize and soybean crops. Starting with $N_s = N_f + N_t + N_h$, NRI_{ms} for the entire system is calculated as:

$$NRI_{ms} = (N_{mg} + N_{sg})/(N_{fm} + N_{fs} + N_{tm} + N_{ts} + N_{hm} + N_{hs}) \quad (2)$$

where N_{mg} = N removed in maize grain, N_{sg} = N removed in soybean grain, N_{fm} = N fertilizer for maize, N_{tm} = N uptake for maize in control N plots, N_{hm} = inorganic N in the control plots for maize, N_{fs} = N fertilizer for soybean, N_{ts} = N uptake for soybean in control plots, and N_{hs} = inorganic N in control plots for soybean. Only N removal in the grain was considered because there was total return of residues to the field, as this is common practice with most farmers in Nebraska. Oat grain and some straw were removed as a feed crop, and this was included in the N removal calculation.

In both the short and long terms, residues decay and return nutrients accumulated during the growth period to the soil. In this experiment, all crops in each step of each rotation were present in each year, thus minimizing potential year-by-crop effects that may be present in less comprehensive trials. A short-term assessment of NRI for other studies should, however, consider the differential decomposability coefficient of incorporated residues. When all systems and all crop components in each system are present in the field each year, one can expect year-effect on any specific legume or cereal to be averaged out over time. Although much of the N fixed is used by soybean or clover and never actually reaches the soil N pool, the calculation based on an assumption that N_x is part of N_m does not influence the conclusions. It was assumed that over a 12-yr period with residues returned to the soil, each system approaches an equilibrium level of soil organic matter, and further assumed that there was no additional net loss of N from the system. An estimate of the actual amount of N returned with residues was calculated using the residue dry matter yields of each crop in each season, system, and N-level, and the laboratory analysis of N concentration in each of these samples. The residue N concentrations varied from 0.42% to 1.18%, and the measured values were used to calculate residue N returned (individual data from residue analyses not reported here).

2.5. Weather dependence of NRI

Climatic variables used in the analysis were growing season (April to August) temperature, rainfall, 'biological windows' (BW1, BW2, BW3), and 6-month standardized precipitation index (SPI) beginning March 1. Biological windows are composite variables derived with mean monthly air temperature and rainfall as input variables in the Newhall simulation model (Van Wambeke et al., 1992). BW1 is the cumulative number of days in a year when the soil is dry (< -1.5 MPa) and temperature above 5°C. BW2 is number of days with soil moist (between permanent wilting point and field capacity) and temperature above 5°C. BW3 is number of days with soil moist (between permanent wilting point and field capacity) and temperature above 8°C. In a practical sense, biological windows 2 and 3 signify conditions above threshold with soil temperature and soil moisture that promote biological activity and plant growth. Annual water balance (AWB) and summer water balance (SWB) are outputs from the Newhall simulation model. The standardized precipitation index is a computerized drought index developed by McKee et al. (1993) and is the rainfall difference from the long-term mean divided by the standard deviation. Statistical tests of multiple comparisons and contrasts (Snedecor and Cochran, 1989) were used to analyze the relative N-removal indices within and among the 21 cropping-system/nitrogen-level combinations. Associations of N-removal indices of the various cropping systems with different weather patterns were assessed with correlation and regression analyses.

3. Results and discussion

3.1. Comparisons of NRI and residual nitrate among systems

The concept of N-uptake efficiency and use (Huggins and Pan, 1993; Moll et al., 1982) is extended in

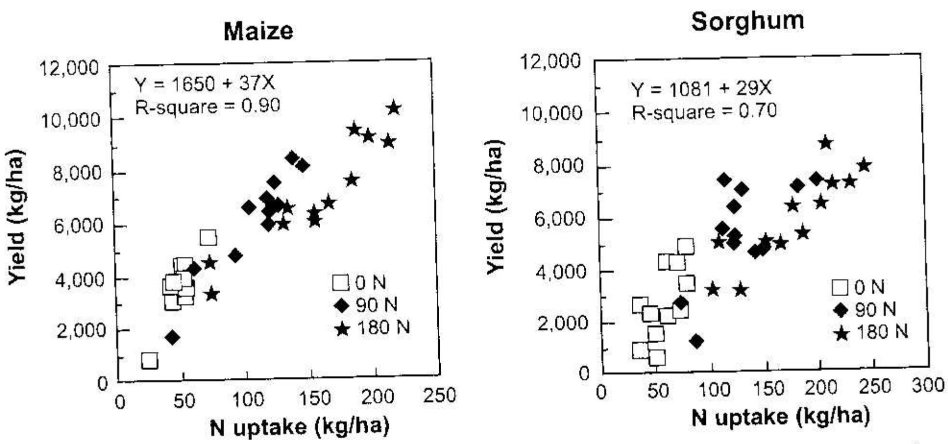

Fig. 1. Relationship between uptake of N into aboveground biomass and grain yields of maize and sorghum; data points from three levels of N fertilization and 12 years presented for each crop.

the present analyses to measure crops' abilities to utilize fixed N and other sources of N (including fertilizer) to produce economic yield. Nitrogen use in these terms is illustrated in Fig. 1, revealing a direct association between N uptake and yields of maize (linear, $R^2 = 0.90$) and sorghum (linear, $R^2 = 0.70$). Higher levels of uptake and thus higher yields were observed at the low (90 kg N ha^{-1} = shaded diamonds) and high (180 kg N ha^{-1} = shaded stars) levels of N fertilizer application, compared to the zero level (shaded squares). Long-term (12-yr) means and variability (standard errors) of NRI from 21 cropping systems–fertilizer combinations are presented in Table 1. At zero N rate, 2-yr and 4-yr rotations used N from the total soil N pool, including fixed N, more efficiently than continuous cereals. Nitrogen-removal index dropped consistently with increasing N fertilizer rates in all but the continuous sorghum systems. Nitrogen extraction was least efficient in continuous sorghum and most efficient in continuous soybean. Standard errors, indicative of year-to-year variability of NRI, were larger in continuous cereals than in rotational systems. From this 12-yr experiment, it appears that rotating maize or sorghum (low NRI) with soybean (high NRI) in a 2-yr alternating sequence with no applied N significantly increases the NRI of the system, although it is still below the level of continuous soybean. Addition of N at a low or high rate eliminated this difference in N use. The 4-yr rotation that includes maize, sorghum, and oat was intermediate between 2-yr rotation and continuous cereal, but only at 0 N rate.

Table 1
Means (standard errors) of N removal index among cropping systems (1984-1995)

System	0 N	Low N	High N
Continous maize (CM)	0.51 (0.02)	0.49 (0.04)	0.42 (0.04)
Continous sorghum (CG)	0.38 (0.04)	0.43 (0.05)	0.37 (0.04)
Continous soybean (CS)	0.73 (0.03)	0.59 (0.03)	0.51 (0.03)
Maize-soybean (M-S)	0.66 (0.03)	0.51 (0.03)	0.43 (0.02)
Sorghum-soybean (G-S)	0.63 (0.02)	0.52 (0.02)	0.42 (0.05)
M-S-G-O/Cl	0.60 (0.02)	0.49 (0.02)	0.40 (0.02)
G-S-M-O/Cl	0.60 (0.02)	0.48 (0.02)	0.40 (0.02)

S.E. = 0.01; M-S-G-O/Cl = 4-yr rotation with maize-soybean-sorghum-oat/clover; G-S-M-O/Cl = 4-yr rotation with sorghum-soybean-maize-oat/clover.

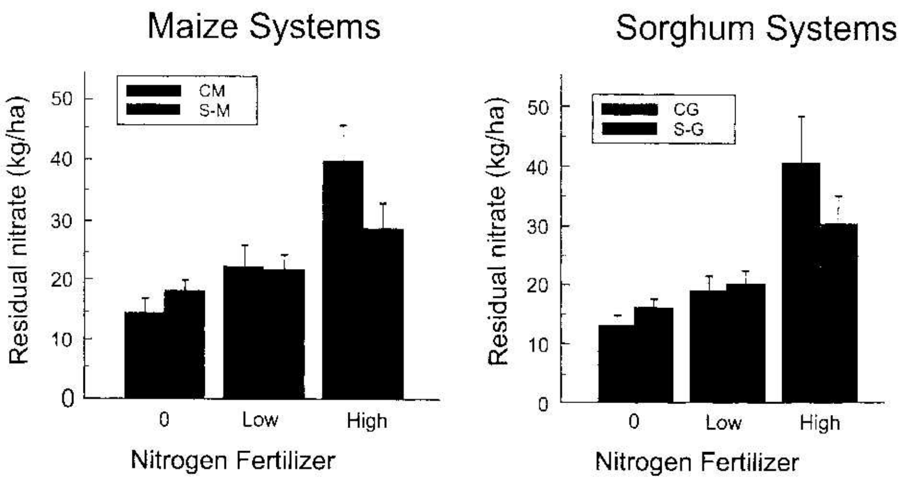

Fig. 2. Relationship between N fertilizer application levels and residual nitrate in the surface 15 cm of soil after harvest; CM, CG = continuous cropping with maize, sorghum; S–M, S–G = 2-yr rotations with soybean–maize, soybean–sorghum (CM, CG fertilizer rates: low = 90 kg ha^{-1} yr^{-1}, high = 180 kg ha^{-1} yr^{-1}; S–M, S–G average fertilizer rates: low = 62 kg ha^{-1} yr^{-1}, high = 124 kg ha^{-1} yr^{-1}).

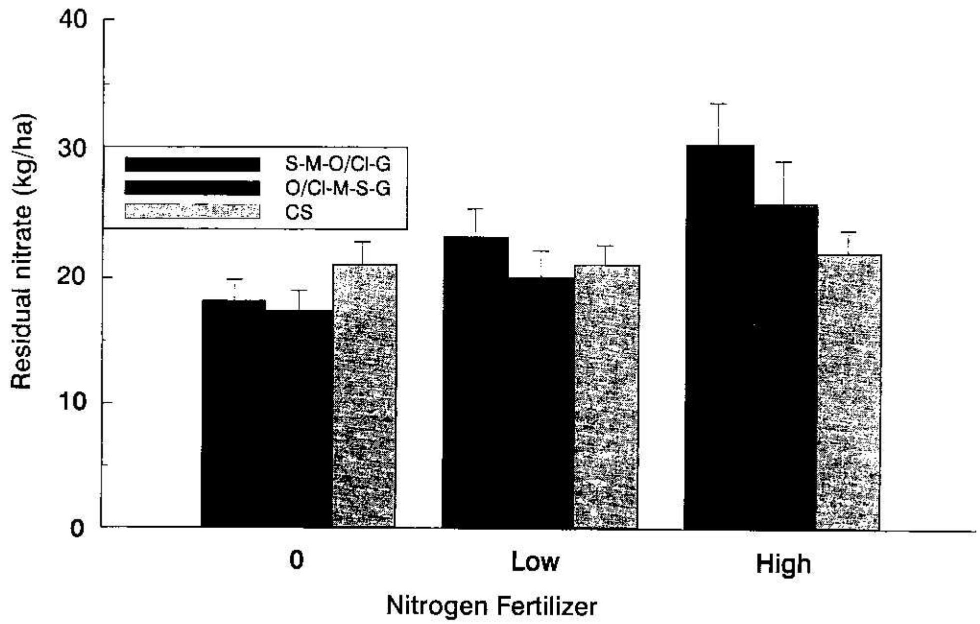

Fig. 3. Relationship between N fertilizer application levels and residual nitrate in the surface 15 cm of soil after harvest; CS = continuous cropping with soybean; S–M–O/Cl–G = soybean–maize–oat/clover–sorghum, O/Cl–M–S–G = oat/clover–maize–soybean–sorghum (CS fertilizer rates: low = 34 kg ha^{-1} yr^{-1}, high = 68 kg ha^{-1} yr^{-1}; 4-yr rotation average fertilizer rates: low = 62 kg ha^{-1} yr^{-1}, high = 124 kg ha^{-1} yr^{-1}.

Results from these system–nitrogen-level treatments help explain why cereal–legume rotations outperform continuous cereals at very low rates of added fertilizer.

As expected, cropping systems with high N removal indices tended to leave little residual nitrate in the soil profile, as illustrated for cereals in Fig. 2. With increased N application, residual nitrate increased in both continuous cereals and 2-yr rotations. The low (90 kg ha^{-1}) and high (180 kg ha^{-1}) rates in the figure represent the N applications during the cereal year in 2-yr rotations and every year for continuous maize and soybean. The apparent lower residual nitrate in a maize–soybean rotation could be due to the lower average annual N application (low = 62 kg ha^{-1}; high = 124 kg ha^{-1}), although this is balanced to some degree by N fixation in soybean every other year.

Continuous soybean provided a different pattern, in that high N fertilization reduced NRI (Table 1) but residual soil N remained at a similar level at all N levels (Fig. 3). Nitrogen fertilizer application reduced NRI in both the 2- and 4-yr rotations (Table 2). Residual nitrate in the soil profile in 4-yr rotations (Fig. 3) was lower than in continuous soybean at 0 N level, but increased with the addition of N, although there was a more frequent presence of a legume (every year in continuous soybean) than in the 4-yr rotation (2 legumes in a 4-yr cycle). Similar to Fig. 2, N rates are confounded with rotation, N application and frequency of legumes in rotations.

Nitrogen-fixing capability of legumes in general is inversely related to soil N concentration. Thus, it is reasonable to assume under the prevailing circumstances that soybean met more of its N needs through fixation in the 0 N plots where N was limiting, but utilized mainly applied and residual soil N in the high-N treatments. In this respect, soybean in the cropping sequence could be viewed as both N source and sink that equilibrate soil N (Varvel and Peterson, 1990). Specifically, in comparison with maize and sorghum, the soybean system raised soil N in plots without N fertilization and reduced it in plots where N was applied (Figs. 2 and 3). According to D.T. Walters (personal communication), soybean depletes soil N unless it is utilized as a green manure crop.

These results indicate both an economic and an environmental cost to following N-fertilized cereals with either maize or sorghum with larger rates of additional N application, without careful soil testing and nutrient budgeting. Purchased N fertilizer must result in economic return to the farmer, and either

Table 2
Contrasts among selected pairs of cropping systems with respect to N-removal index (NRI)

System	Difference in NRI	Probability of significance
Continuous maize vs. continuous sorghum	+0.08	0.0001
Continuous maize vs. continuous soybean	−0.14	0.0001
Continuous maize vs. maize–soybean	−0.06	0.002
Continuous maize vs. sorghum–soybean	−0.05	0.007
Continuous maize vs. M–S–G–O/Cl[a]	−0.02	0.252
Continuous maize vs. G–S–M–O/Cl	−0.02	0.382
Continuous sorghum vs. continuous-soybean	−0.14	0.0001
Continuous sorghum vs. maize–soybean	−0.13	0.0001
Continuous sorghum vs. sorghum–soybean	−0.22	0.0001
Continuous sorghum vs. M–S–G–O/Cl	−0.11	0.0001
Continuous sorghum vs. G–S–M–O/Cl	−0.11	0.0001
Continuous soybean vs. maize–soybean	+0.08	0.0001
Continuous soybean vs. sorghum–soybean	+0.09	0.0001
Maize–soybean vs. sorghum–soybean	+0.01	0.740
Maize–soybean vs. M–S–G–O/Cl	+0.01	0.740
Maize–soybean vs. G–S–M–O/Cl	+0.04	0.030
M–S–G–O/Cl vs. G–S–M–O/Cl	+0.00	0.798

[a] M–S–G–O/Cl = 4-yr rotation with maize–soybean–sorghum–oat/clover.
G–S–M–O/Cl = 4-yr rotation with sorghum–soybean–maize–oat/clover.

crop with too much N could result in a compounding of potential sources of residual nitrate. The present study and previous research at the same location (Clegg, 1982; Varvel and Peterson, 1990) indicate that rotations involving moderate N application (about 90 kg N ha^{-1}) to maize or sorghum and 0 N applied to soybean would be suitable for increasing system efficiency of N use, while reducing risk of nitrate loss from the system. An out-of-sample rotation using data from the current study estimates that NRI of rotations comprising low-N maize and low-N sorghum with 0-N soybean would be 0.59 and 0.56, respectively, as opposed to 0.50 and 0.47 for the same rotations with high-N for both maize and sorghum and 0-N soybean. Although higher yields of maize and sorghum may be achieved at high level of applied N, efficiency of N use is reduced, and more nitrate is available for leaching loss. Varvel and Peterson (1990) and Clegg (1982) suggested that optimum yields in rotations were achievable with an N rate for cereals of about 90 kg ha^{-1}.

Orthogonal contrasts between pairs of cropping systems across all N-levels are presented in Table 2. The NRI values were consistently lower in continuous cereals compared to growing soybean and maize or soybean and sorghum in alternate years. Large significant differences in NRI between continuous crops of sorghum and soybean (-0.22, $P = 0.0001$), and maize and soybean (-0.14, $P = 0.0001$) demonstrate differences among crop capacities to take and/or fix N and put this in the grain. There was no difference in NRI between maize–soybean and sorghum–soybean rotations (0.01, $P = 0.740$). Nitrogen removals by either of the 4-yr rotations were not significantly different from continuous maize (-0.02, $P > 0.25$) but differed significantly from those of continuous sorghum (-0.11, $P = 0.0001$). The analysis further revealed that continuous sorghum removed nitrogen less efficiently than maize (-0.08, $P = 0.0001$), indicating that maize made better use of total N supply.

3.2. Weather dependence of NRI

Weather variables that were significantly related to N removal index are presented in Table 3. Nitrogen removal by maize in the majority of systems was sensitive to the defined biological windows. Significant negative correlations of maize NRI with BW1 represent an effect of drought on soil microorganisms and plant activity, even when temperature is adequate for growth in this high-water-use crop. The only nonsignificant correlation in the maize/BW1 column is for continuous maize (0 N), a situation where N rather than moisture was limiting crop growth and thus N removal. Significant positive correlations of maize NRI with BW2 and BW3 reflect a maize growth and N removal response to length of effective growing season with adequate moisture and temperature for biological activity in the soil. NRI correlations with BW2 are higher than those with BW3 in continuous maize, but lower in 4-yr rotations, indicating that the higher temperature threshold is more important in longer-term rotations. Results from this experiment provided no basis for explanation. Lower absolute r-values for all biological windows with maize NRI at the 0 N level were found in continuous maize and maize in the 2-yr rotation, indicating that weather was less important where another factor in the system was limiting. Highest consistent r-values were in maize following soybean in the 2-yr rotation and low or high fertilizer N-rates. This may represent a more simplistic response to added N in the 2-yr compared to a more complex and attenuated 4-yr rotation, but does not explain why these r-values were higher than in continuous maize.

Correlations of maize NRI with April, May and August temperatures and May rainfall (Table 3) help explain why the biological windows are effective indicators of N removal. Positive correlations of maize NRI with early-season temperatures reveal the importance of early thermal units to crop germination and establishment, although they were significant only for continuous maize. High negative correlations of maize NRI with August temperature in all systems reflect both suppression of maize activity by high temperature during the grain-filling period, confounded with the effects this high temperature has on soil moisture depletion and biological activity during that critical time. Final yield and N-removal data do not provide adequate detail on crop growth and development to help distinguish among the many important and confounded effects of moisture and temperature during the season on both plant development and soil biota.

Table 3
Correlations of weather variables with N-removal index in cropping systems. Weather variables selected based on significance of r [a]

N level	Correlations of maize NRI with						
	BW1[b]	BW2[c]	BW3[d]	April temperature	May temperature	Aug temperature	May rain
CM (0)	−0.38	0.51*	0.46	0.49*	0.62***	−0.70***	−0.24
CM (low)	−0.65**	0.68***	0.64**	0.60**	0.46	−0.93***	−0.44
CM (high)	−0.58**	0.71***	0.60**	0.48*	0.40	−0.83***	−0.41
S–M (0)	−0.50*	0.52*	0.55*	0.00	0.14	−0.33	−0.07
S–M (low)	−0.75***	0.87***	0.81***	0.15	0.22	−0.68**	−0.01
S–M (high)	−0.82***	0.85***	0.86***	0.38	0.34	−0.77***	−0.15
O/Cl–G–S–M (0)	−0.53*	0.56*	0.64**	0.22	0.42	−0.43	−0.03
O/Cl–G–S–M (low)	−0.65**	0.68***	0.75***	0.18	0.14	−0.55*	−0.12
O/Cl–G–S–M (high)	−0.52*	0.54*	0.64**	0.10	0.24	−0.41	−0.06
S–G–O/Cl–M (0)	−0.59**	0.62**	0.70***	0.14	0.28	−0.50*	−0.11
S–G–O/Cl–M (low)	−0.60**	0.66**	0.74***	0.18	0.26	−0.54*	−0.22
S–G–O/Cl–M (high) N	−0.69***	0.66**	0.80***	0.31	0.19	−0.62**	−0.12
	Correlations of soybean NRI with						
	BW1	BW2	BW3	May temp	Aug. temp	AWB[e]	SWB[e]
M–S (0)	−0.65**	0.69***	0.66**	0.56*	−0.43	0.49*	0.53*
M–S (low)	−0.67**	0.74***	0.67**	0.40	−0.57**	0.31	0.46
M–S (high)	−0.64**	0.62**	0.64**	0.47	−0.46	0.52*	0.62**
G–S (0)	−0.61**	0.58**	0.69***	0.45	−0.36	0.42	0.60**
G–S (low)	−0.53*	0.56*	0.68**	0.29	−0.44	0.41	0.50*
G–S (high)	−0.59**	0.46	0.52*	0.34	−0.29	0.20	0.43

[a] Other systems and crops have nonsignificant correlations, including sorghum NRIs.
[b] BW1 = cumulative number of days yr^{-1} with soil dry (< −15 MPa), air temperature > 5°C.
[c] BW2 = cumulative number of days yr^{-1} with soil moist (field capacity), air temperature > 5°C.
[d] BW3 = cumulative number of days yr^{-1} with soil moist (field capacity), air temperature > 8°C.
[e] AWB = annual water balance; SWB = summer water balance.
*, ** and *** denote significance at 0.10, 0.05, and 0.01 probability levels, respectively.
CM = continuous maize, O/Cl = oat/clover; O/C–G–S–M = oat/clover–sorghum–soybean–maize rotation.

Data from these analyses indicate that N removal by maize in rotations was less affected by weather variability than N removal by continuous maize. Soil temperatures in continuous maize may be lower where large amounts of slow-decomposing crop residues act as surface mulch, reflecting radiation and minimizing the direct incandescence of solar radiation on the soil surface. Higher preseason temperatures may prove more beneficial to continuous maize than to rotations where maize follows soybean or oat/clover and there is less residue on the soil surface. This could explain some of the observed differences in correlations between continuous maize and the same cereal in rotation, although the calculations of biological windows were based on air temperature; soil temperatures in the several treatments were not available. BW2 and BW3, based on favorable water and temperature levels, are positively correlated with N-removal in maize; they are useful indicators of soil biological activity as suggested by Van Wambeke et al. (1992) and Waltman et al. (1996).

Soybean N-removal index correlations were similar in most ways to those of maize. Soybean NRI was negatively correlated with BW1, illustrating the importance of a full season of adequate soil moisture and a temperature conducive to biological activity. Positive BW2 and BW3 correlations with soybean NRI demonstrate the same effects, with no apparent difference between the two indices, thus their threshold levels. Because soybean is seeded from late May to early June, the crop is generally not limited by

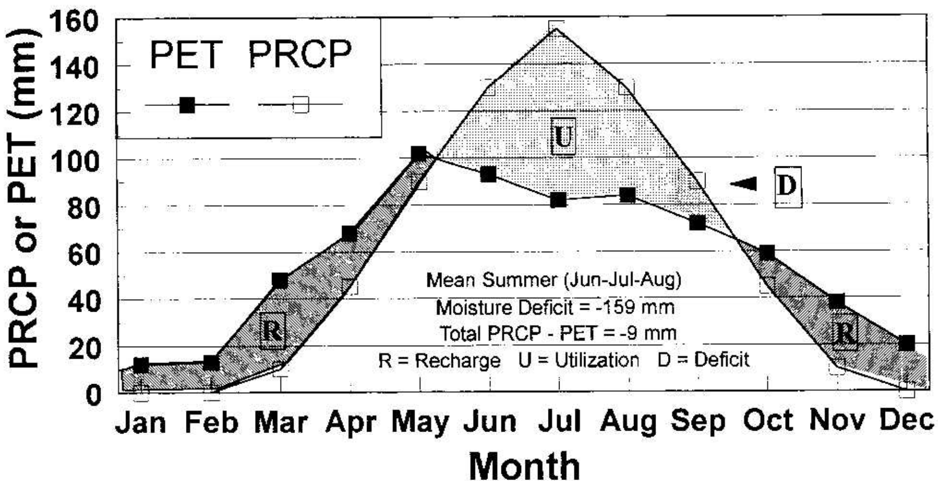

Fig. 4. Moisture balance for Agricultural Research and Development Center, Mead, NE, based on a period of 1969–1995 [PET calculated by Newhall Simulation Model (Van Wambeke et al., 1992)].

temperature in the early stages. This is reflected by the lack of significance in most correlations with May or August temperatures, although the consistent positive correlations in May indicate an importance of rapid early growth with higher temperatures, and the negative correlations in August indicate the influence of high-temperature induced stress during pod fill. The overall importance of soil moisture to soybean N removal is shown by the consistent positive correlations of NRI with annual (AWB) and summer water balance (SWB). There were no significant correlations of continuous soybean NRI with any of the biological windows nor with the temperature or water balance variables.

There were also no significant correlations of any of the sorghum NRI values with biological windows or component weather data. At least as measured by ability to remove nitrogen, it can be concluded that sorghum is less sensitive than maize or soybean to variability in either moisture or temperature. The influence of residue from continuous sorghum, higher than from other preceding crops in the rotations, in retarding soil warming in the spring may be similar to that of continuous maize described above. Lack of significant correlations preclude an in-depth evaluation of differences among sorghum systems in this trial.

What are the implications of different N removal levels among crops and cropping systems? Long-term (1969 to 1995) climate records reveal moisture deficits for crops in June, July and August, and a moisture surplus in April and May (Fig. 4). It is logical that higher potential for loss of nitrate through the soil profile will coincide with the time of low N demand by crops and high rainfall in April and May. In 4-yr systems where a winter cover crop (clover) was in the field in one of four years, the clover served as a scavenger of residual N and helped to deplete spring moisture that would otherwise have accelerated downward movement of nitrate. When incorporated, this green manure eventually releases nutrients to subsequent crops. Soybean makes similar contributions to rotation systems, as the residue may immobilize and release N to the soil pool in a shorter time frame than maize or sorghum residue, although the mechanism of summer and perennial legumes are different (Green and Blackmer, 1995). Low levels of residue following soybean do expose the soil surface, compared to the cereals that leave more residue in the field, and there may be more soil moisture loss through evapotranspiration and more erosion. Results from the current research (lower levels of soil nitrate in rotation systems) support the observations of Schepers (1988) that legumes in rotation could sequester residual N and minimize potential for groundwater pollution.

Table 4
Proportion of variation (R^2) of N removal index explained by combination of indices and specific monthly data

System	0 N	Low N	High N
	Weather index and variable: August temperature + August SPI		
CM	0.53**	0.87***	0.70***
CS	0.44*	0.43*	0.37
M-S	0.23	0.64**	0.67***
	Weather index and variable: biological Window 2 + May temperature		
CM	0.56**	0.58**	0.57**
CS	0.48**	0.55**	0.39*
M-S	0.27	0.76***	0.76***
G–S–M–O/Cl	0.42*	0.46*	0.31
M–S–G–O/Cl	0.42*	0.45*	0.44*

*, **, and *** denote significance at 0.10, 0.05, and 0.01 probability levels, respectively.
CM = continuous maize, CS = continuous soybean, CG = continuous sorghum, Cl = oat/clover, G–S–M–Cl = sorghum–soybean–maize–oat/clover rotation.

These several weather-related indices (biological windows, standardized precipitation indices) can be used in combination with monthly temperature or rainfall data to predict the efficiency of N removal (measured by the NRI). Two examples of this are presented in Table 4. The combination of August temperature and standardized precipitation index for August explained 53% to 87% of the variation in NRI in continuous maize, and up to 67% of variation in NRI in maize–soybean rotation (high N rate). Four-year rotations and sorghum systems were not linearly affected by these two variables. The combination of BW2 and May temperature explained up to 58% of variation in NRI in continuous maize, up to 76% of variation in maize–soybean rotation, and up to 55% of variation in continuous soybean. Lower, although significant, values for the 4-yr rotations indicate that more diverse systems in this experiment were less sensitive to early season temperature, and also to the adverse impact of high August temperature on N-removal index. This may be due to indeterminate growth in soybean or an unexplained buffering in the system that this experiment could not detect.

An important influence on the total N pool in the soil, and thus the nitrate available to crops in continuous plantings or in rotation, is the amount of N that is returned to the soil with crop residues each season in each system. Due to the different types of crops in rotation, e.g., maize and soybean, there are large differences in residue dry matter returned when this is accumulated over a period of years, compared to continuous culture of cereals. Over the 12 years of the experiment, the average amounts of residue returned to the soil in seven cropping systems and at three N levels are presented in the first three columns of Table 5. The amount of stover returned varied from 2780 kg ha^{-1} yr^{-1} in continuous soybean with no N fertilizer to 6570 kg ha^{-1} yr^{-1} in continuous sorghum with the high level of added N. Residue N content varied with both crop and applied N level, with a range from 0.42% to 1.18%; the highest value comes from the sorghum residue component (residue in all treatments analyzed in laboratory but data not shown). When the residues returned per year are multiplied by the appropriate residue N concentrations, and these data aggregated for the various systems from continuous crops to 4-yr rotations, it is possible to estimate the average amount of N that is returned to the field in each of the seven systems and three N levels each year. These estimates are presented in the last three columns of Table 5. There is a range from 16 kg ha^{-1} yr^{-1} in continuous maize with no N applied to 80 kg ha^{-1} yr^{-1} in continuous sorghum with high level of applied N. When these data are multiplied by 12 years in the experiment, there are large differences in added residue N that contribute to the soil nitrogen pool. The differences in residue N among systems and applied N-levels must be considered along with other long-term

Table 5
Annual amounts of residues returned to the field and estimated amounts of nitrogen returned to the soil with these residues[a]

System	Residue (kg ha^{-1} yr^{-1})			Nitrogen (kg ha^{-1} yr^{-1})		
	0 N	Low N	High N	0 N	Low N	High N
CM	3930	5620	6460	16	34	56
CG	4480	6050	6570	28	57	80
CS	2820	2850	2780	24	24	25
M–S	4420	4960	5040	25	35	41
G–S	4740	4900	5200	38	50	58
M–S–G–O/Cl	4780	5460	5660	31	42	52
G–S–M–O/Cl	4630	5170	6000	33	46	54

[a]Residue N content varies from 0.42% to 1.18% in stover dry matter, depending on crop and N level.
S.E. (residue) = 55.0; S.E. (nitrogen) = 1.1; CM = continuous maize, CS = continuous soybean, CG = continuous sorghum, O/Cl = oat/clover, G–S–M–O/Cl = soybean–maize–oat/clover–sorghum rotation; M–S–G–O/Cl = maize–soybean–sorghum -oat/clover.

changes in the soil N situation when considering the impacts of cropping system and N-level on soil nitrate and potential for loss by leaching through the soil profile.

4. Conclusions

The results of this 12-yr experiment demonstrate the use of a nitrogen uptake model to quantify N removal by continuous cropping and rotation systems involving maize, soybean, sorghum and oat/clover. A nitrogen removal index (NRI) was defined as the proportion of N that leaves the field with the crop, compared to the total soil N and fixed N available to crops. There was a significant linear correlation between N removal and grain yields of maize and sorghum. NRI was higher at 0 applied N rates, and higher in rotations than in continuous cereals. Removal as a proportion of the total N pool was greatest in continuous soybean, and least in continuous sorghum. Variability in NRI was highest in continuous cereals than in crop rotation of cereals with soybean or oat/clover. Those systems with higher values of N removal also left less nitrate in the soil that is available for loss by leaching or surface erosion. The data provide a useful index for comparing both N use by different cropping systems and potential for negative environmental impacts when N in the field is not used by crops.

Weather variables also contribute to crop growth, productivity and thus the crops' potentials to take up, transform, and provide N in the harvestable grain that is removed each year. Nitrogen removal was negatively impacted by the same factors that influence crop growth; drought in the early part of the season and during the grain fill period, and high temperatures (confounded with drought) during grain fill. Adverse weather for crop growth was relatively less important in treatments (e.g., 0 N application) where nitrogen supply is limited to crop growth and grain production. Combinations of weather indices can be used to predict a large proportion of the variation in N removal by crops.

Crop residue is an important component of the system that contributes to the soil N pool. In this study, residue returned to the soil system varied from 2780 to 6570 kg ha^{-1} yr^{-1}, accounting for annual additions of 16 to 80 kg N ha^{-1} yr^{-1}. When this is considered along with other residual N sources that remain in the soil after crop harvest, especially in a year with adverse weather and low crop production, it is essential that farmers carefully assess both potential for N loss and the crop nutrient needs for the next season. Farmers can take advantage of soil organic N reserves created over years of residue decomposition in the field. When there is adequate N for the next year's crop, it is not advisable to apply more N than will be used by cereals, and thus will only contribute to potential for loss from the field environment. Rotations including legumes provide a route to N-sparing practices (less N applied over a period of years), compared to continuous cereals. According to the results of this experiment, such rotations can reduce the year-to-year variability in N removal index, as well as the need for applied nitrogen for crop production.

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